Abhijit Saha and Lucas M. Macri

Abstract

The decades-long quest to obtain a precise and accurate measurement of the local expansion rate of the universe (the Hubble Constant or H_0) has greatly benefited from the use of supernovae (SNe). Starting from humble beginnings (dispersions of ~ 0.5 mag in the Hubble flow in the late 1960s/early 1970s), the increasingly more sophisticated understanding, classification, and analysis of these events turned type Ia SNe into the premiere choice for a *secondary* distance indicator by the early 1990s. While some systematic uncertainties specific to SNe and to Cepheid-based distances to the calibrating host galaxies still contribute to the H_0 error budget, the major emphasis over the past two decades has been on reducing the statistical uncertainty by obtaining ever-larger samples of distances to SN hosts. Building on early efforts with the first-generation instruments on the *Hubble Space Telescope*, recent observations with the latest instruments on this facility have reduced the estimated total uncertainty on H_0 to 2.4 % and shown a path to reach a 1 % measurement by the end of the decade, aided by *Gaia* and the *James Webb Space Telescope*.

Contents

A. Saha (✉)
Kitt Peak National Observatory, National Optical Astronomy Observatory (NOAO), Tucson, AZ, USA
e-mail: saha@noao.edu

L.M. Macri
Department of Physics and Astronomy, Texas A&M University, College Station, TX, USA
e-mail: lmacri@tamu.edu

1   Introduction

In this article we take a somewhat chronological view through the process of establishing type Ia supernovae (hereafter, SNe Ia) as standard candles, and the developments, sometimes quite dialectic, which shaped our present-day understanding of the precision and accuracy with which they serve as indicators of luminosity distance. Progress has been dramatic and rapid over the last three decades, driven first by the race to resolve the dichotomy between the "long" and "short" distance scales and the consequent discord over the Hubble Constant (H_0) that divided investigators into at least two distinct "camps." In Sect. 2 we sketch the state of the subject before the advent of the *Hubble Space Telescope* (*HST*) and trace the growing promise of SNe Ia as standard candles, and how finer characterization of their light curves and spectra produced improved determinations of their peak luminosity.

HST has been essential for applying SNe Ia as standard candles to measure H_0. The history and evolution of our understanding has been related in this article in "early" and "recent" sects. (3 and 4 respectively): the two authors of this article, AS and LM, have been respectively associated with these two periods. There have been, and continue to be, points of difference in the interpretation of these experiments. The object of this article is to lay these out in the spirit of dialectics and allow the reader and future investigations to resolve the remaining questions.

2   The Distance Scale Problem Before *HST*

Before the advent of *HST*, which produced a tenfold increase in spatial resolution compared to ground-based imaging (corresponding also to a hundredfold increase in contrast against the background for a point source), there were two distinct classes of distance indicators to galaxies. Those close enough to be anchored by distance measurements within the galaxy were referred to as "primary," while those that required calibration using measurements in external galaxies but could probe to larger distances were called "secondary." Examples of the former are the Cepheid period-luminosity relation (hereafter, PLR; Leavitt and Pickering 1912), RR Lyraes, and detached eclipsing binaries (DEBs), while the latter include the Faber-Jackson, Tully-Fisher, and $D_n - \sigma$ relations and the tip of the red giant branch (TRGB) and

the surface brightness fluctuation (SBF) methods. The goal then (as it is now) was to measure distances that were far enough to probe the "smooth" Hubble flow, i.e., where the peculiar velocity perturbations over the expansion velocity of the cosmic manifold become negligible. The problem was enunciated succinctly in Sandage and Tammann (1974), where they embarked upon the task of refining the calibration of various secondary distance indicators, using Cepheid-based distances available at the time, to galaxies out to the M81 group. From the ground, the goal of reaching to distances where the Hubble flow is undisturbed was not realizable.

In his seminal paper, Kowal (1968) showed that type I supernovae (hereafter, SNe I) in the Hubble flow had a dispersion of ~ 0.6 mag and expressed "[...] considerable hope that the magnitudes of type I supernovae, at least, can be used as distance indicators [...] visible at great distances." His work had to necessarily assume a value of H_0 estimated by other means since no absolute calibration of SNe existed at the time. In closing, the author stated that "[...] distances of the parent galaxies of the nearer supernovae may soon become available through studies of Cepheid variables, HII regions, or red supergiant stars." The possibility of SNe as secondary distance indicators was very attractive because of their large luminosities and the promise that at least one class could have homogeneous light curves (Pskovskii 1967). Oke and Searle (1974) summarized spectroscopic work on this field, drawing attention to the great similarity in the spectra of most SNe I even as they evolve in phase. This provided further interest and rationale in using them as standard candles.

Perhaps the earliest attempts to estimate H_0 directly from SNe were those by Branch and Patchett (1973) and Kirshner and Kwan (1974), who applied the Baade-Wesselink method to types I and II, respectively. Both studies were suggested by L. Searle, who discussed the method in Searle (1974). However, SNe were not among the viable secondary distance indicators at the time due to the lack of fundamental distances to their hosts (Tammann 1974).

It is well known that when observing a magnitude-limited sample of any standard candle (which is typically the case), the intrinsic scatter in its luminosity causes only the brighter ones to be included in the sample as one approaches the observed magnitude limit. The resulting bias, called the Malmquist bias, is an important consideration for interpretation of the Hubble diagram. There is a similar bias due to observational scatter in the measured brightness, which in principle can be mitigated by better observations. However, the Malmquist effect is due to the *intrinsic* scatter in the luminosity, and is a property of the standard candle itself, and standards that show low or negligible scatter in their intrinsic properties are therefore preferred. Sandage and Tammann (1982) argued that the Hubble diagram from a subsample of SNe I, chosen in elliptical galaxy hosts at high galactic latitude to minimize extinction from either galactic or host-galaxy dust, showed a very small dispersion consistent with the prevalent measuring errors of the time. Urged on, therefore, by the promise of having a distance indicator virtually free of Malmquist bias, they proceeded to establish a calibration for absolute peak brightness for SNe I using the brightest blue and red stars in two host galaxies: IC 4182 (SN 1937C) and NGC 4214 (SN 1954A).

Beginning with Elias et al. (1985), a further distinction was made within the SNe I class based on their infrared light curves. The more common of these were now labeled type Ia, while others which have slower declining light curves were labeled type Ib. This work demonstrated that SNe Ia were potentially (pending a larger sample of unambiguous members) very good standard candles in the infrared, with scatter below 0.2 mag. Recognition of the spectroscopic differences within SNe I at optical wavelengths and spectroscopic criteria for identifying SNe Ia were developing at approximately the same time (e.g., Uomoto and Kirshner 1985; Wheeler and Levreault 1985) and were reviewed in Harkness and Wheeler (1990).

The Asiago Supernova Catalog (Barbon et al. 1989) was very influential in the compilation of light curves, and in the creation of photometric templates for SNe Ia. Aided by theoretical understanding of SNe Ia in addition to the observed near-homogeneity of their light curves (a standard B band template light curve was available from Cadonau 1987) and spectra, as well as the low observed scatter in the B and V band Hubble diagrams (Branch and Tammann 1992; Leibundgut and Tammann 1990), it was argued that the peak brightness of SNe Ia should serve as standard candles with intrinsic scatter of only ∼0.25 mag. This claim would be severely tested, challenged, and refined in the years to come, but it was a driving force at the time and already hinted at a standard candle with potentially less scatter than all other secondary indicators. By virtue of their extreme luminosities, SNe could reach farther than the other distance indicators and directly into the smooth Hubble flow. Yet, there were still no known *bona fide* SNe I with adequately recorded light curves in galaxies within reach of Cepheids from the ground.

There were two additional attempts of note to determine the absolute peak brightness of SNe I, now restricted to SNe Ia, before Cepheids in their host galaxies could be identified with *HST*. Leibundgut and Tammann (1990) related the light curves of nine SNe Ia in galaxies in the Virgo cluster to an adopted distance for the cluster to obtain M_B (max) = −19.79 ± 0.12. The distance to Virgo was then (and to some extent even today continues to be) a matter of debate. Branch (1992) calculated the peak brightness from nickel production and radioactive decay where a SN Ia explosion "is thought to be the complete thermonuclear disruption of a carbon-oxygen white dwarf that accretes matter from a companion star until it approaches the Chandrasekhar mass."

The state of understanding of SNe Ia and their light curves just before the launch of *HST* is summarized in Branch and Tammann (1992). There were other efforts in progress, whose results would emerge after the first Cepheid-based calibration of SNe Ia peak luminosity was obtained. The increasing availability of digital detectors throughout the late 1980s and early 1990s enabled the collection of larger, better-sampled, and more homogeneous sets of light curves in multiple filters; chief among these were the Calán-Tololo survey (Hamuy et al. 1993, 1995, 1996b) and the CfA survey (Riess et al. 1999). These would lead to refinements in light curve analysis, whose discussion is deferred to a later section.

Of parallel interest is the use of core-collapse SNe as distance indicators; this continued to develop with a thorough study of SN 1979C in M100 by Branch et al. (1981), who obtained a ∼15 % estimate of the distance to this galaxy. Unfortunately,

any determination of H_0 from this object was subject to even greater uncertainty given that the infall into the Virgo cluster was poorly constrained at that time. SN 1987A was the subject of intense scrutiny, and in the following years, the "expanding photosphere method" was further refined Baron et al. (1995); Eastman et al. (1996); Schmidt et al. (1992), including a determination of H_0 with roughly equal ~10 % statistical and systematic uncertainties (Schmidt et al. 1994).

3   Early Efforts with *HST*

The development of *HST* led two teams to propose large programs to determine H_0. The "*HST* Key Project on the Extragalactic Distance Scale," initially led by Aaronson and Mould, undertook a comprehensive calibration of multiple secondary distance indicators (for a critical review of these methods, see Jacoby et al. 1992). The other team was led by Sandage and Tammann who, motivated by the promise of SNe Ia, focused on their Cepheid-based calibration believing that they would outperform the competing secondary indicators. Their arguments are best stated in Sandage et al. (1992). Sandage and Tammann (1993) presented Hubble diagrams using historical data on nearby SNe Ia in three different passbands (*pg*, *B*, and *V*), showing how the scatter diminished going toward redder passbands. They surmised that the effects of uncertain host-galaxy reddening diminish with increased wavelength and help to reduce the scatter, dropping from $\sigma = 0.65$ mag in m_{pg} to only $\sigma = 0.36$ in V. They argued that by extension the intrinsic scatter is even smaller than the value for V, which effectively makes them free from Malmquist bias. Their Hubble diagrams did not include objects with peculiar spectra or signs of having significant reddening, an approach that they would refine later.

There was at the time a great rift among investigators relating to the determination of H_0. The exposition of Sandage and Tammann through their classic series of papers in the 1970s sought to establish $H_0 \sim 55$ km s^{-1} Mpc^{-1}, but were contradicted by others (well summarized in de Vaucouleurs 1993; van den Bergh 1992). One of the most contentious issues between the so-called long- and short distance scales was about the importance and role of the Malmquist bias, and the other about the role of reddening. That SNe Ia could remove the Malmquist bias from the equation was one of its key attractions, the other being that it could probe distances much further out and determine the deceleration in the cosmic expansion. The plans of both teams were hindered by the spherical aberration in the *HST* primary mirror: point sources were imaged with a sharp core, but with a large fraction of light going into an extended skirt around the core, with structure that lacked azimuthal symmetry. It would be a few years before the flaw could be mitigated with a repair mission.

3.1   Imaging with WF/PC

Despite the significant problems introduced by spherical aberration, the Sandage-led collaboration proceeded to discover and measure Cepheids in the two nearest

then-known SNe Ia host galaxies: IC 4182 (SN 1937C) and NGC 5253 (SN 1972E and SN 1895B). The first to be done was IC 4182 (Saha et al. 1994; Sandage et al. 1992), where the Cepheid V and I PLRs were used to derive a dereddened distance modulus of 28.36 ± 0.09 mag (4.7 Mpc) and a consequent value of M_V (max) $= -19.72 \pm 0.13$ mag for SN 1937C, using previously published photometry of its light curve in the *pg* and *vis* systems. The Cepheids and their colors are consistent with those observed in the Large Magellanic Cloud (LMC), lending confidence in their measurement. The inferred distance was found by Saha et al. (1994) to be consistent with an estimate based on the TRGB. The preliminary resulting value for H_0 was 52 ± 9 in the usual units. Soon after this, the source material for the light curve of SN 1937C was critiqued, and concerned conflicting takes on the color response of the *vis* photometry (Pierce and Jacoby 1995; Schaefer 1996). Pierce and Jacoby (1995) measured a light curve from previously unused V emulsion imaging of SN 1937C by Baade and Zwicky, whose results were also debated between Schaefer (1996) and Jacoby and Pierce (1996), who gave a revised value of $H_0 = 66 \pm 5$. The Cepheid-based distance of Saha et al. (1994) to IC 4182 has never been challenged: Gibson et al. (2000) obtained an identical value and it is in agreement with later determinations of distance to other members of the Canes Venatici group of galaxies to which IC 4182 belongs (Karachentsev 2005). Both the Cepheid distance and the supernova light curve are consistent with zero extinction, as gleaned from their colors. While in IC 4182 the reddening effects are small and essentially negligible, the complications with the treatment of reddening began to show themselves with the next target. Ideally, one would like to have an unreddened/unextinguished or true distance modulus to the host galaxy, which involves correcting for both the foreground extinction within the Milky Way and extinction in the host galaxy. A similar correction is then also needed for the supernova, which may in general suffer different host-galaxy extinction (further complicated because we now know that the total-to-selective extinction toward SNe Ia can be quite different from the galactic reddening law). Each set of corrections bring their own uncertainties, which in special circumstances, one might be able to finesse. Different investigators may not agree on the assumptions needed for such mitigation and fall back on the formally correct way for consistency, bringing along the attendant uncertainties in their full form.

The Cepheid distance to NGC 5253 (Saha et al. 1995) was beset by a higher degree of crowding and confusion, and by the absence of longer period (and hence brighter) Cepheids. They reported an apparent distance modulus of $(m - M)_V = 28.08 \pm 0.10$ mag and argued that SN 1972E would have suffered the same extinction. From the (photoelectric) supernova photometry by Ardeberg and de Groot (1973), it was surmised that M_V (max) $= -19.50 \pm 0.21$ mag. Saha et al. (1995) argued that the TRGB distance from I-band photometry from the *HST* WF/PC images was consistent with the apparent modulus, and within the measurement errors, with near-zero reddening from the host galaxy (and $E(V{-}I) \sim 0.08$ mag of foreground galactic reddening). It was argued that SN 1972E, which is far from the center of NGC 5253, would suffer no more reddening from within the host galaxy than the Cepheids. Gibson et al. (2000), in re-deriving the distance from

the same data (with additional observations from WFPC2) obtained a true distance modulus of $(m - M)_0 = 27.61 \pm 0.11$ mag. Further comparison of the derived peak luminosity of the supernova is complicated by different source light curves and treatment of reddening and is beyond the scope of this review, but can be had by a detailed reading of Gibson et al. (2000) and references therein. It is also worth noting that the photometry of the same data yielded results within expected possible differences (of a few hundredths of a magnitude), and the difference in distance moduli was driven by differences in the Cepheid samples used. The Cepheids in common to both studies yield the same results, but each study used a nonoverlapping set of Cepheids compared with the other, and it is the differences in these samples that drives the different final distance moduli, as noted by Gibson et al. (2000). These issues would reappear later, sometimes in more striking ways, as host galaxies increasingly farther away were investigated with a repaired HST.

3.2   Improvements in Classification of SNe Ia

By the time *HST* was serviced, with WFPC2 replacing WF/PC and curing the imaging pathology due to the misshapen primary mirror, there were several other refinements taking place regarding our state of knowledge of SNe light curves and spectra. The first of these was by Phillips (1993), comparing the decline rate of SNe Ia light curves characterized by the quantity $\Delta m_{15}(B)$ (the decline in brightness in the B band in the first 15 days after B maximum) to their absolute peak magnitudes estimated from distances to their host galaxies via the Tully-Fisher relation or the SBF method. He surmised that faster-declining SNe Ia are intrinsically fainter than the ones that decline slowly. This echoed earlier work on SNe light curve properties by Pskovskii (1977). If the light curves of the Cepheid-calibrated SNe Ia differ from those that define the Hubble diagram, the Phillips relation necessitates a systematic correction. A meme emerged that SNe Ia were not standard candles, but "standardizable" candles (even though the meme is never applied to Cepheids, which have an analogous period dependence). At about the same time, the results of the Calán-Tololo survey (Hamuy et al. 1993), monitoring light curves and spectra of $0.01 \lesssim z \lesssim 0.1$, lead to unprecedentedly clean Hubble diagrams (Hamuy et al. 1995). The detailed light curves permitted the study of differences within the type Ia subclass in a larger sample, and with more precise scrutiny.

In a seminal paper, Hamuy et al. (1996a) re-derived the peak luminosity vs. $\Delta m_{15}(B)$ relation using light curves from the Calán-Tololo survey in the smooth Hubble flow: relative distances to them were assigned according to recession velocity. A definitive dependence was derived, but with a slope very much more muted than the original Phillips relation; the reason for the difference in slopes likely lies in the fact that the distances assigned by the recession velocities have far less scatter than those from secondary distance indicators. Using their relation, the scatter in the Hubble diagram from SNe Ia was reduced to $\sim$0.15 mag rms (see Table 3 of Hamuy et al. 1996a, for details) for objects that did not show excessive

reddening. Riess et al. (1995) and Riess et al. (1996) presented a novel technique to simultaneously fit photometry in multiple passbands based on a linear model of corrective templates, derived from the light curves published by Hamuy et al. (1995) and Riess et al. (1999). This so-called multicolor light curve shape method (MLCS) was the first to simultaneously determine the luminosity correction and measure the reddening to a given SN Ia, yielding Hubble diagrams with reduced scatter.

There were also other correlations that came to light: SNe Ia were on average brightness in late-type galaxies (e.g., Hamuy et al. 1995; Riess et al. 1999); their luminosities correlate with color at maximum light (e.g., Tripp 1998); and the more luminous SNe Ia also show higher ejection velocities as measured by the Doppler shift of the blue edge of calcium absorption (e.g., Fisher et al. 1995). While these diagnostics correlated among themselves for the most part, it was also clear that subtyping within the SNe Ia class was not a one-parameter affair. In particular, the decline rate relation still fails to account for all the objects with very steep decline rates ($\Delta m_{15}(B) > 1.7$): e.g., Hamuy et al. (1995) pointed out that SN 1992bo and SN 1991bg, which have very similar (but large) values of $\Delta m_{15}(B)$, differ in absolute peak brightness by nearly 2 mag. The spectra of these two SNe however show significant differences.

Branch et al. (1993) classified SNe Ia spectra into three subcategories: (i) those with time-evolving spectra that resemble those of SNe 1981B, 1989B, 1992A, and 1972E; (ii) those like SN 1991T, which at early phases show "unusually weak lines of SiII, SII, and CaII but prominent features of FeIII"; and (iii) those like SN 1986G and SN 1991bg, which show absorption features of TiII. Of the 84 spectra classified by them, 83 % were in the first, "normal" category (later literature refers to this spectroscopic subclass as "Branch normal"). They also recognized subtle variations in spectra within the subclasses and that all of the spectra could be arranged in a sequence, with SN 1991T at one extreme, followed by the "normal" SNe, and finally by the third category. At the time, SN 1991T was in a class by itself, with all the rest of the "peculiar" SNe being like SN 1986G and SN 1991bg. Branch et al. (1993) also noted that the spectral sequence parallels the light curve decline rates, with SN 1991T as the slowest, and SN 1991bg and SN 1986G among the slowest. Interestingly though, SN 1992bo has "normal" spectra, and quite distinct from the spectra of SN 1991bg, whose light curve declines only slightly faster than SN 1992bo, defying any claim that the distinctions among the SNe Ia can be characterized as a single-parameter family. The decline rate vs. luminosity relation for only the "Branch-normal" SNe Ia from the Calán-Tololo survey is only half again of that derived by Hamuy et al. (1996a), since it samples a restricted range of $\Delta m_{15}(B)$, where the dependence is shallow.

3.3   The WFPC2 Era

Cepheid distances to farther host galaxies, using the repaired *HST* with WFPC2, were obtained as soon as the camera became available: NGC 4536 (SN 1981B;

Saha et al. 1996a), NGC 4496F (SN 1960F; Saha et al. 1996b), and NGC 4639 (SN 1990N; Saha et al. 1997), where the SNe were all "Branch normal," and relatively slow decliners. In Saha et al. (1997), the authors constructed a Hubble diagram with SNe Ia recession velocity satisfying $3 < \log v < 4.5$. They applied a color cut for peak brightness color (after correcting for foreground reddening within the galaxy) $-0.25 < (B - V)_{max} < 0.25$, meant to bracket the intrinsic color range within which the Branch-normal SNe Ia layer, and also at the same time reject SNe Ia that were highly reddened due to host-galaxy extinction. The SNe Ia with Cepheid distances thus far also satisfied this criterion. The decline rate relation for a subsample chosen this way was derived independently and used to de-trend both calibrated SNe Ia and those that probed the Hubble flow. Parsing the data in multiple ways, including using a restricted sample to spiral galaxies only, they obtained H_0 values close to 60, in the usual units. A prescient statement appears in their paper: "A most unexpected result is that distant SNe Ia in spirals ($3.8 < \log v < 4.5$) are fainter than the nearer ones ($3.0 < \log v < 3.8$) by 0.27 ± 0.13 mag in B and 0.16 ± 0.12 mag in V. Even if SNe Ia are *good* standard candles, this is contrary to all selection effects that bias the most distant SNe Ia to be overluminous."

With the paucity of available SNe Ia hosts that could be reached with WFPC2, the next results were from two interesting cases. SN 1989B in NGC 3627 (Saha et al. 1999) was a Branch-normal SNe Ia, but one with high yet *known* host-galaxy reddening. It could be added to the calibrators after explicitly accounting for the host-galaxy reddening. SN 1991T in NGC 4527 (Saha et al. 2001b) exhibited a very slow decline rate and was studied to examine how its peak luminosity differed relative to other objects in the decline-rate vs. luminosity relation. Both these galaxies, viewed nearly edge on, exhibit extreme stellar crowding and *differential* internal reddening, which likely affected the photometry of the discovered Cepheids. For SN 1991T, no large difference in luminosity with respect to the other Cepheid-calibrated SNe Ia was seen, but crowding effects could have resulted in underestimation of the supernova luminosity. For SN 1989B, the reanalysis of the same data by Gibson et al. (2000) would produce very discrepant results: as in the case of NGC 5253, the cause revolves around differences in the Cepheid samples and in the way reddening is treated, even though the photometry of individual Cepheids in common hardly differ between the two studies. A new SNe Ia, SN 1998aq in NGC 3982, and within range of WFPC2 photometry, became available, and a Cepheid distance was obtained (Saha et al. 2001a).

In addition to the increasingly finer categorization of SNe Ia described above, there were also emerging questions about the accuracy and universality of the Cepheid PLR. Kennicutt et al. (1998) measured a metallicity dependence for the zero point of the PLR, by measuring Cepheids in both inner and outer regions of M101, which have very different attendant metallicity as measured from the gas-phase emission lines. Even though the size and even the sign of the metallicity dependence continue to be debated, consideration of the metallicity of the Cepheid progenitor population has become necessary. Combining all the elements of systematics discussed above, Sandage et al. (2006) summarized the results of their

team's investigations, with a best estimate for H_0 of 62.3 ± 1.3 (stat.) ± 5 (sys.). This contrasted somewhat with the results from the overall Key Project result from Freedman et al. (2001) of 72 ± 8 km s^{-1} Mpc^{-1}, which was by now heavily weighted by the Gibson et al. (2000) reanalysis of the Sandage et al SNe Ia sample. The key differences arose not from the photometry, but from sample selection for Cepheids (see Sect. 3.1) and treatment of reddening (see Sect. 3.4).

3.4   Unsolved Issues Awaiting Further Studies

With the progressive improvement in our understanding of the relative luminosity of SNe Ia as gleaned from the residuals in the Hubble diagram, with scatter less than 0.15 mag, the focus of systematic uncertainties turned toward uncertainties in the Cepheid distance scale. Both the Sandage team and the "Key Project" team based their final results assuming/asserting a distance modulus to the LMC of 18.50, with further corrections for metallicity dependence from the empirical study by Kennicutt et al. (1998). Alternate results were available (e.g., Romaniello et al. 2006), which contest the magnitude and even the sign of the metallicity dependence. Implicit in all of these is tacit assumption that the helium-to-metal ratio ($\Delta Y / \Delta Z$) has no cosmic variance, since such a variation can drive very significant changes in the luminosities of Cepheids (Fiorentino et al. 2002).

The mechanics of performing the photometry and discovering and measuring Cepheids in the WFPC2 images brought several issues to surface that even today do not have definite solutions. The combination of stellar crowding and undersampling of the stellar PSF by these detectors may well have resulted in systematic measurement bias that affected the work of both the Sandage and the "Key Project" teams. Artificial star tests (Ferrarese et al. 2000; Saha et al. 2000) indicated that the effects were not severe. However, for Cepheids in NGC 4536 (Saha et al. 1996a), there is clear evidence that individual Cepheids with higher-quality light curves result in larger dereddened distances than from those with poorer light curves (see Fig. 7 in Saha et al. 1996a).

A key issue is that of correcting for reddening to the Cepheids. Madore (1982) constructed the so called Wesenheit relation, which combines the P-L relations in two (or three) distinct passbands into one relation that effectively marginalizes the reddening. Freedman et al. (2001) used a Wesenheit relation uniformly for all their distance determinations. Sandage et al. (2006) argued that application of the Wesenheit relation has the net effect of interpreting all color excesses/anomalies in the Cepheid photometry as reddening, and chose instead to treat each galaxy by what they considered optimal. They argued that application of the Wesenheit relation to correct for reddening can amplify both intrinsic color variations and any systematic measurement biases (see Fig. 11 in Saha et al. 1996a). A more detailed critique can be found in Saha (2003). These effects become progressively stronger as distance to the galaxy under study increases, implying that such hidden systematics affects more distant galaxies with increasing severity. They are neither fully systematic, nor random, rather they come from the effect of measurement biases that are amplified

through the application of other systematic corrections. Szabados and Klagyivik (2012) review several sources of uncertainty in the Cepheid PLR, several of which may be lensed unfavorably through the Wesenheit relation.

There has been a trend in later literature to disregard SNe Ia with light curves from the pre-CCD era; however there have not been suitable SNe Ia nearer than the Virgo cluster since the advent of CCDs (with the exception of SN 2011fe in M101). Is there a trade-off between more accurate distances to nearer SNe Ia with less certain photometry on the one hand, and accurate photometry but poorer distances to SNe Ia that are farther away? The case of SN 2011fe illustrates the problem. This object erupted after a multitude of distance estimates of M101 from Cepheids and TRGB measures using *HST* data were already in the literature. Matheson et al. (2012) showed that the derived distances from these various studies span a range of 0.5 mag in distance modulus. Even if the reddening to the supernova were understood perfectly, the derived value of H_0 could be held hostage to the disagreements over the distance modulus to M101. This highlights the danger of relying on a small number of calibrators and the importance of ensuring consistent absolute calibrations of different primary distance indicators and critical comparisons of their relative distances over overlapping ranges.

4   Recent Efforts

The discovery that type II "plateau" supernovae could also be turned into "standardizable candles" (Hamuy and Pinto 2002) led to significant reductions in the scatter of the Hubble diagrams for core-collapse SNe (Olivares et al. 2010). A promising recent extension of this technique (Rodríguez et al. 2014) found 8–9 % uncertainties in relative distances, but its application to H_0 is still limited due to the very small number of calibrating objects (four in that publication).

A precise geometric distance to the nearby spiral galaxy NGC 4258 (Herrnstein et al. 1999) and the installation of the Advanced Camera for Surveys (ACS) onboard *HST* motivated an independent calibration of the Cepheid PLR by Macri et al. (2006). This work also highlighted the impact of an increasingly more precise and accurate value of H_0 for constraining the properties of dark energy. At the same time, ACS was also used by Riess et al. (2005) to improve the absolute calibration of SNe Ia by obtaining a Cepheid distance to NGC 3370 (host of SN 1994ae). That paper also presented the first photometry for SN 1998aq and a determination of H_0 based on a reanalysis of all "ideal" SNe Ia to date, a rather small sample of four objects with low reddening, well-observed light curves starting before peak light, decline rate within a well-defined "normal" range, and photoelectric or CCD-based photometry.

In mid-2006, Riess and Macri established the "Supernovae and H_0 for Equation of State of dark energy" (SH0ES) project with the goal of significantly reducing the uncertainty in H_0. A modest reduction in the statistical uncertainty was obtained by increasing the sample of host galaxies to six "ideal" SNe Ia (Riess et al. 2009b). More importantly, a significant improvement was obtained in the systematic

uncertainty by constructing a sturdier distance ladder that minimized or eliminated many of the sources of uncertainty that plagued the WFPC2-based studies.

SH0ES based its Cepheid distances on near-infrared (H-band) observations of these variables, which are preferred to optical measurements for several reasons. The intrinsic scatter of the PLR decreases significantly, thanks to the reduced effect of the finite temperature range of the instability strip, the impact of reddening is diminished by factors of ~6 and ~3 relative to V and I; variations in Cepheid luminosity as a function of chemical abundance are predicted by all models to reach a minimum in this passband. The absolute calibration of the Cepheid PLR was based on the maser distance to NGC 4258. Since all the photometry was on the same system, thanks to the use of a single telescope (*HST*) and well-calibrated modern cameras, this "differential ladder" reduced $\sigma(H_0)$ to 5 % (Riess et al. 2009a). Furthermore, this work emphasized proper accounting and full propagation of *all* sources of statistical and systematic uncertainty via a matrix approach.

The installation of the Wide-Field Camera 3 as part of the last servicing mission to *HST* greatly improved the observatory's near-infrared capability. Soon after becoming available, the SH0ES team used this instrument to obtain Cepheid distances to two additional SN Ia hosts and to greatly increase the number of Cepheids with homogeneous near-infrared photometry in the anchor galaxy and the previously studied SN hosts. Further improvements on the absolute calibration of Cepheid luminosities were possible, thanks to the availability of DEB distances to the LMC and HST-based parallaxes to Milky Way Cepheids, leading to $H_0 = 73.8 \pm 2.4\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $\sigma(H_0) = 3.3\,\%$ (Riess et al. 2011). Since then, the SH0ES team has been carrying out a large observational effort to more than double the number of Cepheid distances to "ideal" SN Ia hosts (now 19) and to obtain parallaxes to additional Milky Way Cepheids using new *HST*-based techniques (Riess et al. 2014). Helped by independent advances on a refined distance to NGC 4258 (Humphreys et al. 2013), an improved DEB distance to the LMC (Pietrzyński et al. 2013), an 8× larger sample of LMC Cepheids with near-infrared photometry (Macri et al. 2015), a large sample of M31 Cepheids with *HST* photometry (Kodric et al. 2015), and ~300 SNe Ia in the Hubble flow ($0.023 < z < 0.15$), the uncertainty in H_0 has been reduced to 2.4 % (Riess et al. 2016).

5   Conclusions

The full potential of type Ia supernovae as distance indicators is finally within reach, thanks to the efforts of many individuals and teams during the past five decades. As a result, SNe Ia have played a key role in ever more precise and accurate determinations of H_0.

We are now able to perform a critical test of the assumed "standard" cosmological model (ΛCDM, $w = -1$, $N_{\mathrm{eff}}^{\nu} \simeq 3.046$, $\sum m_\nu = 0.06\,\mathrm{eV}$) by comparing the directly measured local expansion rate (based on Cepheids and SNe Ia) with the *predicted* value based on observations of the cosmic microwave background (CMB) and baryon acoustic oscillations (BAO). Presently, there is "tension" between the

direct and inferred values of H_0 at the $1 - 3\sigma$ level depending on the set of CMB observations that is adopted. If confirmed at higher significance, this difference could hint at Physics beyond the standard model such as an additional source of dark radiation in the early universe. While we await results from Stage IV CMB and BAO experiments, the Cepheid-based calibration of SNe Ia luminosities marches toward a goal of 1 % total uncertainty by 2020 based on *Gaia* discovery and parallaxes of thousands of Cepheids to dramatically improve the galactic PLR, another doubling of the number of SNe Ia hosts with *HST*-based Cepheid distances, and *JWST* NIR observations of Cepheids in all hosts to reduce photometric errors due to crowding.

6   Cross-References

▶ Cosmology with Type IIP Supernovae
▶ History of Supernovae as Distance Indicators
▶ Low-z Type Ia Supernova Calibration
▶ The Peak Luminosity-Decline Rate Relationship for Type Ia Supernovae
▶ Type Ia Supernovae

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